"HISTORY FRIENDLY" SIMULATIONS FOR MODELLING INDUSTRIAL DYNAMICS

Christian Garavaglia

Eindhoven Centre for Innovation Studies, The Netherlands

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Department of Technology Management

Technische Universiteit Eindhoven, The Netherlands

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Christian Garavaglia

CESPRI, Bocconi University, Milan, Italy
and
Cattaneo University, LIUC, Castellanza (VA), Italy

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1. Introduction[1]

During the last years an increasing number of simulation models has emerged. In a short length of time, this kind of models as well as conferences and workshops about simulation techniques and agent-based modelling have proliferated in a lot of fields of the social sciences, like sociology and economics, and also in the natural sciences, engineering, mechanics, and manufacturing.

Considering the economic thinking, it is possible to state that simulation methodologies have represented both a new way of studying and a new way of modelling the industrial economics' features. The aim of this paper is to give a new contribution to the simulation modelling in industrial dynamics and, in particular, to put some order in the very new branch of studies called "History-friendly" simulation models, emphasising their original aspects and their way of developing the structure of the models.

This new generation of simulation models has been mainly used by the so called evolutionary economists to analyse the evolution and the dynamic aspects of modern economies. Specifically, the so called "History-friendly" evolutionary modelling focuses its attention on the qualitative theories regarding the mechanisms underlining the evolution of industries, with the help of formal modelling in order to represent routines, relationships and behaviours of economic agents. The declared purpose is to *"[…] capture the gist of the appreciative theory put forth by analysts of the history of an industry or a technology, and thus enable its logical exploration"* (Malerba *et al.*, 1999).

So, first of all, it is necessary to analyse what are the main basic features of the evolutionary theory (specifically of the industrial dynamics approach) and what are its most important characteristics, i.e. it is necessary to specify what is the field within which the simulation techniques are applied.

After having specified the theoretical framework of the industrial dynamics thinking, the second step of this work requires to explain why simulations represent a useful tool of analysis for this kind of theories, and what are the purposes that a similar way of study aims to reach.

The work is structured as follows: the first section examines the main features of the industrial dynamics approach. The second one aims to explain what the basic characteristics of the simulation methodology are and what are the benefits of using simulations as a tool of analysis for modelling the theories under exam; in particular we focus the attention on the so called "History-friendly" simulations. The third section gives some details about the object-oriented type of programming. The fourth part points out some useful examples of simulation techniques. Finally, some conclusions and remarks are stated.

[1] A very first draft of this paper has been written after many discussions and joint works with Luca Berga in 1999, to whom I am particularly indebted and grateful. I would also like to thank for their useful suggestions: Franco Malerba, Luigi Orsenigo, Nicola Lacetera, Daniela Grieco, Marco Gazzola.

2. The Theoretical Framework of Industrial Dynamics

The evolutionary economics theories and the industrial dynamics approach started to proliferate after the publication of the seminal work of Nelson and Winter *"An Evolutionary Theory of Economic Change"* in 1982. During the 1980s and 1990s an increasing interest in the evolutionary economics' field has emerged: many hundred papers have been published, a lot of new specific questions have raised, and several new reviews have born specifically focusing on the evolutionary economics' themes.

It is certainly possible to trace back the origins of the evolutionary thinking to the birth of the economic thought. Eminent economists, like Alfred Marshall and Joseph Schumpeter, recognised in their works the centrality for economic studies of the dynamic aspects of industries and the importance of paying attention to the evolution of industrial sectors, but for different reasons their intuitions have been shelved for years until the recent renewed attentions and developments embodied in the evolutionary economic thinking.

Mainly the lack of reality of which the orthodox theories were accused, and the more and more explicit recognition of the importance of the dynamics in the modern societies caused a shift in the interest of many economists to a different approach, that permitted to focus more intensively on the dynamic aspects of the economies. In fact, the orthodox approaches of study that dominated the economic research in the last decades have been characterised by a tendency to a static approach of analysis, and to a formal mathematical modelling, regardless of the dynamic and evolutionary aspects of the economic environments and agents. Moreover, the dominance of the analytical side pushed the economists to disregard the empirical field of analysis. In addition, the ambitions of evolutionary academics to address new economic topics, to bring to light new ones and to examine old ones from different perspectives played an important role (see also Silverberg, 1997).

The importance of the dynamic aspects and the need for taking into account the continuous processes of change of modern economies represented a primary stimulus for the evolutionary economists to prosper. Since the 1970s and 1980s Nelson and Winter started to define a secure ground and indicate a trajectory for simulation models (Andersen and Valente, 1999; Kwasnicki, 2003; Silverberg and Verspagen, 1995a; Silverberg, 1997). Along this tradition, among the numerous significant developments of the evolutionary approach, there is the recent increasing implementation of simulation models in order to understand the characteristics and the complexity of the industrial process of continuous change. We claim that this family of models can be considered to have a crucial role in what has been called by Bottazzi *et al.* (2001) and Windrum (2004) the "second generation" within the expanding literature of the evolutionary thinking (Malerba *et al.*, 1999). With regard to this, it is possible to recognise two different complementary methods of proceeding: on the one hand, there are models that aim at identifying potential invariances and generic basic properties of industrial structures and dynamics without focusing on specific sectoral characteristics. On the other hand, there are the "History-friendly" models, that are based on a detailed rigorous illustration of a specific industry, adding in this way *"richer, history-based, phenomenological details to the formal representation"* (Bottazzi *et al.*, 2001).

The core characteristic of the "History-friendly" simulation models is to put together a deep understanding of the historical events of an industry evolution (being in this way what we mean with "being closer" to the real world), and a formalisation of the relationships that govern the behavioural routines, with the purpose of capturing the dynamics and the evolution of both the economic system and the interaction of the economic agents. Formal evolutionary models strongly contributed to the understanding and the exploration of the logic of the economic evolutionary processes. Some of them paid attention to the consistency of their logical explanation and the empirical stylised facts to be explained. Some others, on the other way, represent a more abstract approach, and lesser attention has been paid to the empirical phenomena they claim to model. The aim of "History-friendly" models is to provide a theoretical tool that could engage in dialogue with the logic examination and the causal explanations presented by the empirical studies.

It is clear, then, both that a lot of divergences makes the evolutionary approaches very different from the orthodox thinking, and that among these approaches the "History-friendly" models characterise themselves as an attempt to capture empirical details with the help of a formal representation. More precisely, "History-friendly" models are, on one hand, formal models, being in this way a well suited tool for logical explorations and causal argumentation, making the logic that guides model's results explicit. On the other hand, they are appreciative theories, being empirically oriented and relating to verbal argument put forth by many evolutionary scholars. A first conclusion on the meanings of adopting a simulating approach for studying industrial dynamics is *"in general that verbal argument is sufficiently complicated that a simulation model is the only way through which its gist can be captured formally"* (Malerba *et al.*, 1999).

The purpose of this section is that of pointing out what are the main characteristics of the evolutionary theory, and on what ground the need for "History-friendly" modelling has emerged.

2.1. Different Levels of Industrial Dynamics

It is possible to recognise three different levels of analysing industrial dynamics[2]. The first level, called "Specific dimensions of industry dynamics", refers to a series of stylised facts that have been studied and put in evidence by several empirical and theoretical studies. We could also broadly name this level of analysis as "industrial demography". The analysis focuses on the specific aspects of industrial dynamics, and the purpose is to understand the determinants of these empirical regularities.

[2] In what follows we relate to Malerba F., Orsenigo L. (1996), "The Dynamics and Evolution of Industries", *Industrial and Corporate Change*, Volume 5, Number 1

More precisely, industries are characterised by high grades of turbulence, by different structures, by different rates of change in the technological knowledge, and these differences seem to be persistent. The same could be said about firms in an industry. Firms are heterogeneous with regard to many aspects, and the differences persist over time: dimension, performance, survival probability, growth rates, innovative activity are only few examples of heterogeneity among them.

A lot of studies in this field has emerged in the last years. Jensen and McGuckin (1997) propose an empirical model that shows the high level of heterogeneity among firms; Geroski and Jacquemin (1988) show the persistence of profits over time; the investigation of the so called Gibrat's law has received much attention among the economists during the past decades (see for example Sutton 1997); Audretsch (1995) examines the turbulence level of industries relating it to the technological regime; the regularities regarding the technological change and environment are deeply analysed by, among the others, Pavitt (1984), Malerba and Orsenigo (1995), Winter (1984). In a theoretical model Jovanovic (1982) explains the simultaneity of entry and exit, the differences in firms' growth rates and the persistence of these differences, the coexistence of expanding efficient firms with declining inefficient ones, and the smaller scale of entrants in comparison with the incumbent firms, assuming heterogeneity among firms.

The second level, called "Structural dynamics", relates to a joint analysis of the dynamics of the main structural variables that characterise an industry. We refer explicitly, then, to the joint analysis of the evolution of the concentration ratio over time, the rates of entry and exit of firms and their innovative activities of product and process innovation over the evolutionary pattern of the industry. The most well-known model with regard to this kind of analysis is the "Industry Life Cycle" model. Klepper (1996) investigates the evolution of industrial sectors and points out the existence of different phases in the evolution. Each phase is characterised by a different number of firms competing in the market, different R&D strategies, different entry and exit rates and product or process innovation activity (see also Jovanovic and MacDonald, 1994).

The final level, "Structural evolution", takes into account a broader view of analysis. In addition to the aspects examined by the first two levels, we look now at the evolution of the industry as a whole, studying the emergence of new products and technologies, of new skills and competencies of the firms, the definition and the related changes in the firms' boundaries, learning processes, the diversification and integration strategies, the emergence of networks and the role of the public authorities and institutions. Such an attempt brings obviously a higher degree of complexity into the analysis. The joint investigation of many different aspects, of their evolution and of the subsequent relationships that emerge among them clearly needs a flexible and powerful tool of analysis that could make possible to capture the complexity of the economic system as a whole and the co-evolution of its aspects over time. Such situations seem not to be tractable applying traditional analitycal methods. The simulation techniques, then, appear to be the best option for the economist that aims at such a complex analysis of the evolution of industrial sectors.

Moreover, most of the aspects cited above, like firms' boundaries, the importance of networks, learning processes and the role of institutions seem to be very industry specific. A deep understanding of these phenomena, then, requires a close and particular representation of the characteristics of the specific sector considered.

On the one hand, then, we recognise that appreciative theories bring to light how economies are characterised by non-linearity, stochastic dynamics, heterogeneity, uncertainty, interaction, bounded rationality and coevolution. On the other hand, these characteristics are highly industry-specific, such that we need to study the history of a particular industry in order to be able to capture the mechanism and processes that govern its evolution. What we suggest here is the utilisation of "History-friendly" simulation models as a useful way of studying and understanding industrial dynamics, in order to grab hold of complexity and to depict a clear and deep representation of the distinctive details tailored to particular industries (Malerba *et al.*, 1999; Andersen, 2001). Certainly, the goal of "History-friendly" methodology goes beyond the analysis of a given industry: looking for invariances, conditions and factors responsible for the results of different simulation models, pertaining to different industries, will enable the researcher to rise a very interesting inductive exercise thinking about the generalisation of the models and results.

3. Simulations and Industrial Dynamics Models

3.1. The Simulation Methodology

Simulation techniques have widely proliferated during the past years in many fields of the social sciences. The aim of this section is to briefly describe some basic features of this methodology that we are considering in the definition of the "History-friendly" simulation models.

First of all we claim that can identify the objective of our simulations models in the experimentation and exploration analyses. With experimentation and exploration we mean the possibility of reproducing in laboratory an artificial industry, made by artificial agents and environments, in order to investigate and explain some phenomena that happen in the real world. With regard to this, we are able to manipulate some variables and characteristics of the model that we might not be able to do in the real environments. In this way we are able to go into the model in order to understand what are the factors and the fundamental processes that make the model behave as it behaves. Tests of validity and counterfactual analyses, then, emerge. From this point of view, then, simulations represent an investigative device.

Conte (1997) mentions at least five reasons for developing simulation models: in presence of agents that are able to "learn", in the analyses regarding the "emergence" of new phenomena from the interaction of the modelled agents, in the studies of evolution and adaptation of systems, in cases of complex aspects, and in presence of an explorative aim of studying. In analysing industrial dynamics, and in particular with reference to the third level of investigation, "Structural evolution", we have to face all the situations mentioned above. The challenge of "History-friendly" models is to cope with these difficulties and to give a result of the research that more closely resembles the complexity of the real world.

Axtell (2000) argues that there are at least three reasons for using agent-based simulations in the social sciences, with regard to their complementary role to algebraic modelling (see also Richiardi, 2004). *"The first use is numerical computation of analytical models"*, the second relates to the capability of *"testing the robustness of analytical models with respect to the departures from some of the assumptions"* (Richiardi, 2004), and the third use consists in the development of stand alone simulation models. While the first two reasons are complementary to the algebraic modelling, the third is a substitute, aiming at developing a structured model that captures the various relationships and mechanisms that simultaneously define the economic environment under exam.

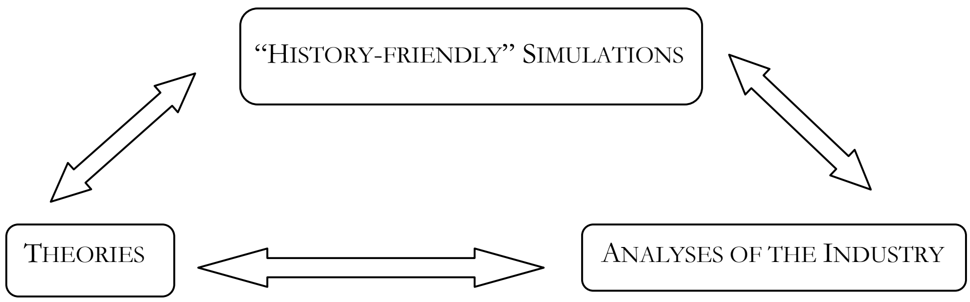
The characteristics of this family of simulation models leads directly to the development of the theory that we want to model and to the emergence of the main questions that we want to answer. More precisely, in order to represent an artificial industry and to be able to carry on analyses on it, we need to understand why we want to model the phenomenon and what are the principal aspects that we have to take into account. We need a theory that represents the behaviours of the agents in the model, and the responses of the environments to the interaction of those behaviours and to any changes in them.

3.2. The "History-friendly" Simulation Models

First of all, it is necessary to point out that what we mean with "History-friendly" simulations is not the numerical analysis of complex formal models, whose analytical solution is difficult to derive. We define "History-friendly" models as stand alone simulation models, precisely specified and formally structured, build upon the definition of "interacting objects". The focus here is on the development of what we call *objects*, that could represent agents as well as environments of the specified economic system. In order to do this, we make use of an "object-oriented" language for programming the model. We will come back later to this point.

It is clear from the discussion above that the ground on which "History-friendly" models are developed is twofold. On one hand, we need a deep understanding and analyses of the industry we are modelling. On the other, we are building our model with regard to any theory that enable us to represent the basic relations and characteristics that we have discovered in the study of the industry. In this way, our simulations are directly linked to some theories, and moreover simulations contribute to the development of the theories (Figure 1), because they represent a *"[…] systematic way of deducing the implications of a theory as it operates under particular circumstances […]"* (Hannerman R.A., 1995).

Figure 1: Relationship among simulations, theories and industries' studies



In the light of this, we claim here the importance of a three-step analysis in the development of the "History-friendly" models. First of all, the study of the basic features and characteristics of the industry as well as of the agents that populate the industry is needed. This stage of the process of model development is extremely important in order to give the model robustness, credibility and acceptability to its results. In other words, the structure of the economic agents, the choice of parameters and the specification of the characteristics of the model need to come from an accurate empirical investigation, in order to be modelled and fixed as much as possible according to the empirical evidence (for the importance of empirical knowledge for developing simulation models and empirical calibration see also Werker and Brenner, 2004).

If the first step is not anyway theory-free, theory becomes crucial in the second step. This stage is represented by the development of the simulation model in which the industry characteristics are incorporated. The challange is to incorporate the theoretical background into the programming language of the model, in order to represent the basic relationships and structure of the economic environment under examination.

The third step consists in the run of the simulation model, the analysis of its results and the calibration of the model. Moreover, and most importantly, after having obtained the satisfactory specification of the model (in other words, after the calibration of the model that requires the change in the parameters and methods of the model such that the differences between the simulation results and the empirical evidence is minimized), the third step requires to go back to the theories and the history of the industry under exam. We claim that the third step is crucial in order to reach the declared purposes of "History-friendly" modelling: establish a stronger link between formal theory and empirical evidence; understand what are the factors that are responsible for the obtained results; stimulate the debate and learn from the reasoning and discussions; raise questions and work out the hypotheses and results of the theoretical logic.

With regard to this, we claim that "History-friendly" analyses do not only use the inference principles of deduction and induction, but we stress that also the abduction principle is at work in this reasoning (see Werker and Brenner, 2004). *"[…] Abduction consists in studying the facts and devising a theory to explain them. Its only justification is that if we are ever to understand things at all, it must be in this way"* (Peirce, 1867, in Werker and Brenner, 2004). Data collection and empirical analyses are required in order to develop a formal theory that is able to investigate the logic behind them and to make out the structural fundamentals which explain the observations we have.

It is important to stress here that "History-friendly" models do not aim at predictive results. We claim that the goal of this kind of simulating approach is twofold: on one hand, the purpose is analysis and description. In this sense "History-friendly" models try to replicate the industry of interest, describing its main dynamics and relations, and understanding what are the factors and the fundamental processes that make the model behave as it behaves. On the other hand, the purpose is prescription. From this point of view, "History-friendly" simulations are interestingly implemented to study counterfactual analyses. If the former purpose aims at answering to the question "What has happened?", the latter focuses on the question "What might have happened?", stressing what are the conditions we need in order to obtain a given result and pointing out what can be made to happen. Moreover, given that "History-friendly" models are industry-specific, we want to emphasise here that understanding the basic processes of different given industries might enable us to find generalisations, invariances, similarities or distinctions among these industries. The purpose of "generalisation" might raise very interesting inductive exercises pushing the reasoning back to think about what factors and processes are responsible for the evolution of industries.

In the light of what mentioned above, in what follows we propose a series of motivations and reasons that lead us to the adoption of the simulation approach, in particular the "History-friendly" simulations, to study industrial dynamics and evolution.

3.3. Applying Simulation Techniques for Modelling Industrial Dynamics

The fundamental aspect we consider in this section is that the object-oriented simulation techniques, thank to their flexibility and powerfulness, give us the possibility to deeply analyse the basic features of the evolutionary theories and of the industrial dynamics' models.

The strongest critics to the traditional analyses has been the inability to well fit to the complexity of economic systems. One of the possible explanation to this lack might be referred to the too much simplifying assumptions needed in order to analytically manage and solve the models. A lot of complexity, the basic feature for modern economies as we have seen, is lost in the formal modelling definition of behaviours and interactions of economic agents. Obviously, we need to specify some assumptions also in implementing simulations models, but we are now able to analitycally define a larger amount of relations and equations, that enable us to capture a representation of the dynamics of the model that is closer to the characteristics of complex systems.

The need for realism has certainly been one of the most important causes of the evolutionary theories' emergence. In this regard, the simulation models, if build upon a detailed analysis of the economic behaviours at a micro level, represent an attempt to analyse at best the patterns and the processes thought to characterise the economic environment. In this sense, the "demand", that has recently emerged, for a simulating approach comes directly from the need of analysing the more and more dynamic, volatile and changing economic environment, and finds its answer in the rise of this kind of models.

A first important aspect to consider is that the development of simulation models and the inherent formalisation of the relationships, of the variables and of the interactions among these variables, force the economist to better understand some concepts, usually disregarded by a pure analytical approach of study, and to examine thoroughly the dynamic process of evolution. We are referring, for example, to the so called *"rules of thumb"*, that represent a basic feature of the evolutionary economics (Simon, 1982; Cyert and March, 1992). To think about how to structure and how to formalise these "rules of thumb" is, first of all, a good exercise to better understand some economic behaviours and procedures, and secondly is an excellent way to try to keep the model as much as possible near to the real world. The "rules of thumb", in fact, are not usually formalised in the traditional theories. They represent a specific way of doing, trying to depict what happens in the concrete events and behavioural decisions of economic agents, and we are able to incorporate them in our modelling only thank to the flexibility of the simulation methodology.

Moreover, these "rules of thumb", or more generally the *routines*, are the result of a process of learning and adaptation of the economic agents to the environmental shocks and to their changing objectives. It follows that the dynamic pattern of evolution that leads to a specific situation is the ongoing result of what happened in the past history, and on the other side it is extremely important in order to be able to understand the characteristics of the present state of the world, in terms of the main features and variables that constitutes the skeleton of the economic system. Past and present are tied by some dynamic processes of the economic structure. Historical events, then, determine the evolution of the economic system. In other words: *history* matters! Phenomena like *path-dependency* and growth along specific trajectories are widely described by the industrial dynamics approaches, and with the simulation models we want to formalise them and capture their effect and importance for the rest of the economy's functioning.

Another crucial aspect to take into account is given by what we call *complexity*. Complexity and the consideration of the macro (or industrial) level as the result of the repeated interaction of micro heterogeneous agents are two of the basic features of evolutionary theories. It is clear that analysing simple relationships among the economic actors is not difficult to do. But when we move to the examination at the macro level of the whole system there may arise some obstacles for a good understanding. With simulations it is possible to analyse the complexity of the macro level as the result of the repeated interactions of the individual agents. With object-oriented simulations we can model economic agents as defined, as we will see in the next section, by specific and personal endowments-variables and routines-behaviours. From this representation and following the repeated interaction of all the objects in the model, the evolution of the sector emerges. In this sense, we can define the approach of the "History-friendly" models to simulation as "analysis", contra posed to the other main approach "synthesis", as stated in Cohen and Cyert (1961). "History-friendly" models, in fact, are built on an accurate formalisation of the behaviour of the components (i.e. what we call objects) of the system, and their aim is the analysis of the result of the model in order to examine if this outcome fits to the observed behaviour of the over-all system that has been modelled. On this basis, we are able to carry on many theoretical investigations and experiments, like counterfactual and sensitivity analyses.

The study of a complex system, together with the recognition that much of this complexity is due to the *multi-agent interaction* of the system's components, represent one of the main reasons of adopting a simulating approach for modelling industrial dynamics[3]. What we stress here is that starting from the definition and formalisation of the behavioural routines and attributes of the economic agents, we are able to reach an outcome in terms of time paths of the principal endogenous variable at the system level: the organization of interacting agents generate the aggregate structure. More on this shortly.

The result of the simulation runs, then, must be read as the macro (or sectoral) level outcome generated by the micro heterogeneity of the individual objects. The source of the dynamics and evolution of industrial structures, as well as of economic growth, must be found in the heterogeneity of firms and their business units. And the variation in firm performance is not only associated with traditional observables, but more importantly with unobservable factors specific to the firm (Jensen and McGuckin, 1997): our attempt is to model these *unobservable* factors like routines, feedback processes and learning in order to analyse the resulting outcomes at aggregate level. In this way we claim the importance of firms' characteristics in the process of industrial changing and economic growth.

Moreover, we have to observe that some of the intricate nature of the complex systems that we study is related to at least two other factors: first, the fact that the constituting elements of the system themselves *co-evolve*. In the modelling process of

[3] *"[…] economic theory is about agents who not only compute but also interact"* (Andersen and Valente, 1999).

our frameworks, we explicitly recognise the influences that every agent have on the behaviour of other agents: firms interact each other, and they are embedded in a system where other agents like public and other private institutions are involved. It is crucial, in order to understand the evolution of an industry, to capture the co-evolutionary processes that characterise and shape the performances and behaviours of the single agents. Second, the phenomenon of *uncertainty*: economic agents are embedded in an evolving system that consequently is by definition characterised by uncertainty and not perfect predictability of the outcomes of their actions. In the implementation of the simulations, we explicitly consider the fact that part of the result of the decisions undertaken by the agents are due to a random event, that we can indifferently call "luck", "bias" or "random shock". What is important is that firms cannot perfectly foresee the outcome of their actions.

In other words, the most important reason to adopt the simulation mechanism we are discussing here clearly results from the discussion above. The interest of our analysis and the targets of our studies are not directly and explicitly modelled (see among others Ziman, 2000). Rather they emerge from the interaction among the objects of the simulation process: they are the result of the repeated computed interactions of the components of the model. This property of *"emergence"* is then, we claim, the real essence of our simulations. For emergent behaviour we mean *"behaviour not inherent in or predictable from a knowledge of their constituent parts"* (Holland, 1998). We are interested in some observable results that we can study only after having set the parameters and structures of the relevant components of the system, and that implicitly emerge as an effect of their ongoing communication. In this sense, "History-friendly" models, as many other simulation models, could be defined as *"a representational mechanism that is distinguished by its capacity to generate relations that are not explicitly encoded"* (Rasmussen and Barrett, 1995). If we believe that the whole tells us more information and results than the simple sum of its parts, because of the inherent process of change and interaction among them, simulations then give us the possibility to study some phenomena that are generated by the relations incurring among different elements.

In other words, if our goal is to study some emergent phenomena of a complex system then we need to identify some mechanisms and processes that, given the characteristics of the components, give rise to these phenomena. In our cases, these mechanisms are the interaction and the existing relations among the system's components, and the properties of the system as a whole. With "History-friendly" analyses we are interested in these micro-macro relation: we are able to study macro properties of the system as the result of the properties of micro agents and of their interaction, but also as emergent behaviours that are not predictable from knowing only the properties of that micro agents.

So far we have been pointing out the most important aspect that lead us to adopt a simulating approach to model industrial dynamics. To sum up, we have considered realism, dynamics and changing environments, routines and rules of thumb, path-dependency, complexity, co-evolution, uncertainty and multi-agent interactions. Most of the features we have taken into account so far are defined in a nice work by Winter (2000) as *"the immutable principles of evolutionary economics"* (see also Kwasnicki, 2003). As this support, we want to conclude with a provocative point, claiming that simulation models, and more precisely "History-friendly" models, can better formalise and cope with these evolutionary economics' principles rather than other approaches.

4. Economic Agents and Environments as "Objects"

Let us consider now the object-oriented programming paradigm as a way of representing and describing industrial dynamics simulation models. Economic agents and environments could be well stylised by an object-oriented representation: agents could be defined by a set of specific endowments, attributes and routinised behaviours, and environments could be specified by features, attributes and actions.

What we mean with object-oriented modelling is a type of programming in which the programmer defines self-contained entities, that consist not only of data, but also of operations that are applied to the data structure. It follows that the data structure becomes an "object" that consists of variables and functions. The run of the programme consists in the interaction of these independent and idiosyncratic objects, and this interaction leads in the end to the emergence of the results of the model. In other words, we are generating and studying dynamic phenomena that are part of a higher level than the one in which the original elements and objects are defined.

The object-oriented modelling, we claim, is a useful approach to the construction of complex models, in which a system characterised by a large number of actors and economic units can be represented as a set of objects. The results of the model are obtained by letting the computer to simulate the process embodied in the assumptions, that is the characterisation of the objects in terms of their attributes and methods. The results emerge from the complex interaction among these objects: we are able in this way to obtain complex dynamical properties that otherwise might not be tractable. The outcomes are typically obtained in terms of time series of the endogenous variables generated by the model.

Suppose to identify with c a characteristic of an object, let us say an economic agent, and a routinised behaviour with b. We can then formally represent an agent in the model as an array, defined as follows:

$$[c_{1i}, c_{2i}, \ldots, c_{Ci}, b_{1i}, b_{2i}, \ldots, b_{Bi}]$$

where $i = 1, \ldots, n$ represent the i-th agent, C and B are the total numbers of characteristics and routines of the agent. Each c has a particular value for each agent, and similarly each routine can be defined with any singular peculiarity for each agent, so that we can model a population of heterogeneous agents. Obviously any c and b

can be equal to zero for any agent, such that each agent has a different number of features and follows a different set of behaviours. Similarly the environments could be represented as arrays, including their basic distinctive characteristics and their actions.

So, given *n* agents, we could depict the basic starting framework of the model as a matrix of dimension $n \times (C+B)$:

$$\begin{bmatrix} c_{11} & c_{12} & \dots & c_{1C} & b_{11} & b_{12} & \dots & b_{1B} \\ c_{21} & c_{22} & \dots & c_{2C} & b_{21} & b_{22} & \dots & b_{2B} \\ \dots & & & & & & & \\ c_{n1} & c_{n2} & \dots & c_{nC} & b_{n1} & b_{n2} & \dots & b_{nB} \end{bmatrix}$$

This is the basic starting level of the system. It is the interaction of these *n* objects, agents and environments, that leads to the emergence of the global result at the industry level. As we said above, the results are presented in the form of time series of some interesting variables. Let *T* denote the length of the simulation runs, and r_s the s-th of the *R* outcomes considered (i.e. the observable characteristics and properties that we are interested in) with $s=1\dots R$. We can, then, read the results of the model as a matrix of dimension $R \times T$:

Summing up, the simulation process, starting from a dimensional space $n \times (C+B)$, gives an outcome in the space $R \times T$.

$$n \times (C+B) \xrightarrow{\text{SIMULATION PROCESS}} R \times T$$

$$\begin{bmatrix} r_{11} & r_{12} & \dots & r_{1T} \\ r_{21} & r_{22} & \dots & r_{2T} \\ \dots & & & \\ r_{R1} & r_{R2} & \dots & r_{RT} \end{bmatrix}$$

At the stage of programming the model structure, we define which are both the formalisation of the objects, as said above, and the dimensions of the outcome: that is to say, we define what is the appropriate length of time of the simulation runs, and the basic statistics of the variables that we aim to examine, like, for example, the concentration ratio, the amount invested in R&D in the industry, the number of surviving firms and the relative number of products, the number of exiting and entering firms, the number of accords, of mergers and so on.

4.1. Classes, Objects and Instances

Each object in the model belongs to a "class". A class can be defined as a template, a prototype, which describes and gives names to the attributes and the operations (actions). For example, an object modelled as a firm belongs to the generic class named "Firm". Each instance of a specific class will be characterised by the same attributes and operations and by some specific values of the attributes that generate idiosyncratic characteristics and specific operations. As a consequence, it is possible to obtain a set of objects similar by their basic structure which characterise their behaviour but with different sensibilities in the way they behave, due to the idiosyncratic values of their attributes. Moreover, heterogeneity also results from the different evolution that each object experiences during the run of the simulation, given that the attributes' values change throughout the run.

In terms of the object theory, all the objects that are created from the same class are defined as "instances" of that class. We also usually refer to the attributes as the "variables" of the object, and to the operations as the "methods" which define the objects' behaviour.

So, following the firm example, the class "Firm" could have some attributes like budget, production capacity and others endowments, that specify the features of the instanced objects belonging to the class. This class could also have several "methods" such as R&D functions, accounting and marketing procedures, investments decisions and so on, that define the specific behaviour, actions and rule of thumbs of its instanced objects.

4.2. Relations Among Classes

One of the principal advantages of object-oriented programming techniques over procedural programming techniques is that they enable programmers to create modules that do not need to be changed when a new type of object is added. A programmer can simply create a new object that inherits many of its features from existing objects. This makes object-oriented programs easier to modify. We call this kind of relation among classes as "inheritance". Classes may have another kind of relation that link them to other ones, called "encapsulation".

Inheritance. A generic class can be used as a general scheme to generate more specific classes. The class "Firm" can be used, for example, to generate the class "Computer firm", which will inherit all the attributes and operations of that class, with, of course, the possibility of adding new specific characteristics and features. The inheriting class it is not an object and only its instances, as defined above, will produce objects.

The inheritance process is extremely powerful in order to generate complex and specific classes starting from a generic one[4]. It is also a useful instrument that could help to identify common elements between different categories of agents.

In general, it is possible to define a rule-of-thumb to decide if a class can be structured using an inheritance process. To this purpose it is useful to examine the relation between the inherited class and the inheriting one: if the relation is an *"is-a-kind-of"* relation then inheritance is a good strategy. For example mainframes are a kind of computer. As a consequence a potential class named "Mainframe" could be created inheriting the characteristics of the generic class called "Computer product".

Encapsulation. Two classes may also be linked by a *"has-a"* relation. For example, each computer firm has a computer to sell. As a consequence the class "Computer product" is in some way enclosed in the more general class "Computer firm". Clearly it is not possible, and it is not logic, to use an inheritance relation since computers are not a kind of computer firm. By the way, it is clear that some relations between the two classes occur: each computer firm produces a computer product. As a matter of fact it is possible to say that the "Computer firm" class encapsulates the "Computer product" class. The consequence is that the "Computer firm" class contains the set of commands and definition to use in order to make an instance of the "Computer product" class. It is important to notice that the "Computer product" class is not contained in the "Computer firm" class: only the instance process is present in the structure of the class. That is to say, when a computer firm object is instanced, it will also contain an instance for its product. Given this structure, every message sent to a specific computer object must refer to the firm object which own the specific computer object.

4.3. A First Step Towards the Implementation of the Model

It is crucial to identify what are the main basic starting steps we need to follow in the development of a simulation model. As stated by Andersen and Valente (1999) *"the development of the simulation model […] often require[s] very hard work and the developer may still find bugs and add core features after a long period of intense study".* It is crucial, then, to have rigour and clear ideas since the very beginning. In order to facilitate the analysis of the model, we claim that it is important to keep the dimension of the model, i.e. the relevant parameters under control, as small as possible, at least in the first versions of the model.

We believe that it might be useful to go after the following stages:

- classification of basic elements of the system;
- identification of the relationships among agents;
- implementation of the programme;

[4] There are two main kinds of inheritance. Single inheritance, which determine a flow of information from one single class (inherited class) to another single class (inheriting class) and multiple inheritance, used to blend the information from more than one inherited class into a single inheriting class.

- model analysis.

The first step in implementing an object-oriented simulation approach to economic models requires a process of identification of the basic elements of the system, such as environments and agents, with their attributes and operations. This classification activity has the useful effect of subdividing the model into several subsets and helps to identify hidden relations in simple context as well as in complex and dynamic ones.

In order to give to each element the proper role, actors and their relations in the model must be analysed in terms of "who makes what". This means to identify within each environment who are the agents, which are their main "methods" (actions) and attributes, and what are the purposes of the actions.

After the accurate formation of the basic elements of the system it is important to map all the relations and behaviours in order to understand the directions and the intensity of information flows, and the relationships that replicate the complex interactions of the dynamic context. This analysis should be implemented at three levels: relations among environments; relations among agents and relations between an agent and an environment; attributes and operations of each agent.

The aim of the implementing procedure, then, is to have clear in mind the system and all its elements and connections, in order to methodically and meaningfully translate the economic system we want to model into the programming language. This represents the third stage: the translation of the design into the formalisation of the programming language, and the subsequent model execution. This stage is extremely important in order to develop a credible and robust model. As stated in section 3.2. the setting of the parameters' values as well as the development of the relationship among agents are crucial in order to follow the declared purposes of the "History-friendly" simulation methodology.

The final step is given by the model analysis. At this stage we are able to study the theory we are modelling with regard to the industry of interest. This stage represents the most relevant in economic terms: analysing the outcomes of the model, we are able to explore and investigate the logics behind the functioning of the relations among the agents, understanding the meaning and explanations of the relationships, looking for invariances, studying sensitivity analyses. This is the core of the simulation analyses! Moreover, we may be interested in the implementation of counterfactual analyses, focusing on what are the conditions we need in order to obtain a given result.

5. Some Examples of Modelling Complexity

The aim of this section is to show a couple of examples of modelling complexity. We start the discussion by presenting a first example based on the studies of the computer industry. With respect to this, we only give the basic idea in order to show

how it is possible to model the evolution of an industry, to consider the theoretical aspects and how it is possible to open up interesting discussions. Secondly we focus on the evolution of the pharmaceutical industry: we present in more details here how it is possible to model firms' behaviour, analyse highly complex environments and test theories.

5.1. A "History-Friendly" Model of the Evolution of the Computer Industry

The first example we want to study refers to the evolution of the computer industry that faced along its evolutionary process the emergence of a dominant firm in the mainframes market (IBM), the introduction of microprocessors and the subsequent rise of the new market segment of personal computers. The major results of the first version of the model relate to the exploration of the determinants of the achievement of market dominance by one firm in the mainframes that, in presence of substantial changes in the fundamental technologies, has not been able to seize the major share of the new PC market that the new technology opened up (Malerba *et al.*, 1999): the timing of the introduction of the new technology, the greater consumers' lock-in in the mainframe market rather than in the PC market and the greater sensitivity of consumers to the price of computers in the PC market are considered the key factors in determining the evolution of the industry.

As a brief example of the development of the model, we focus here on the crucial object called "Computer Market", which represents the competitive arena, defined by the number of potential customers, where the objects "Firms" compete in order to gain the biggest market share. Firms are represented by sets of technological and marketing capabilities, and by routines of action[5]. Cheapness and performance are the two basic attributes of the products, defined then as an ensemble of characteristics *à la* Lancaster, the combination of which gives a specific level of utility. The greater the utility of a product, the greater the number of this product that is purchased. If we denote with X_1 the "cheapness" attribute and with X_2 the "performance", we can define the merit M (i.e. the level of utility) of a particular computer product as:

$$M=b_0(X_1 - X_{1min})^{b1}(X_2 - X_{2min})^{b2}$$

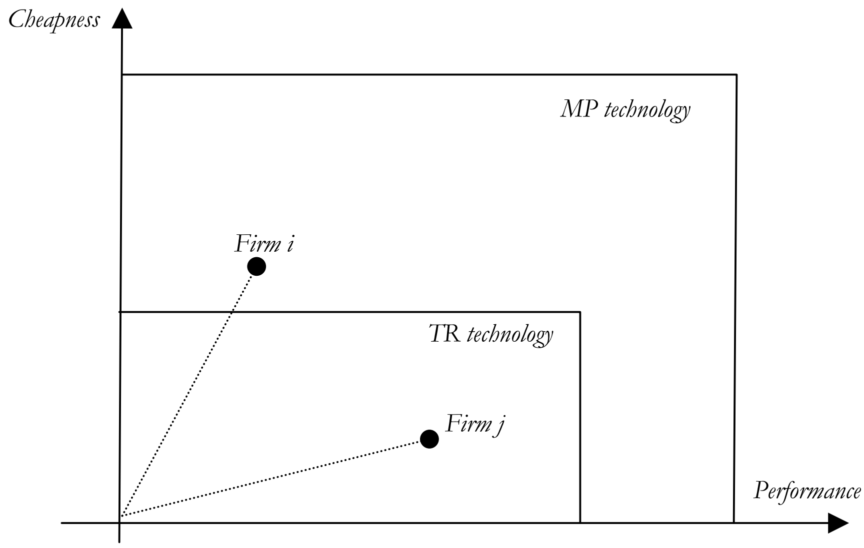
where X_{1min} and X_{2min} are the threshold levels for the two attributes, and b_0, b_1, b_2 are parameters.

In this way, given the existing component technology of the computer (transistor technology, TR, or microprocessor technology, MP), the worth of a product can be seen as a function of the position in the space defined by cheapness and performance (Figure 2). The position in the space of a particular firm is determined by its firm-specific trajectory followed in the evolution of the

[5] We do not focus on the definition of firms here. Rather we concentrate more on the structure of the market (the demand).

technological improvements of its product along the two dimensions cheapness and performance.

Figure 2: Technological limits of computers incorporating TR and MP technology



If a product meets the threshold requirements, then the probability that this product is purchased takes into account also the role of advertising and a brand loyalty effect, other that the merit of the computer. Denoted with M_i the merit of the computer of the i-th firm, m_i the firm's market share, A_i the advertising expenditure for the product, and with d_1 and d_2 two parameters that assure positive values for computers that have just broken into the market, the probability P_i is, then, given by:

$$P_i = c_0(M_i)^{c1}(m_i + d_1)^{c2}(A_i + d_2)^{c3}$$

where c_0, c_1, c_2, c_3, are parameters and c_0 is specified such that the sum of probabilities adds to one. As we said earlier, the greater the merit of a product, the greater the number of units that will be purchased. It follows that, given the number of customers (which are divided into a large number of subgroups), given that the probability that a subgroup purchases a particular computer is defined above as P_i, if customers in a given subgroup buy a particular computer, then M is the number they buy. Consequently we determine in the model the relative sales of each firm and the corresponding market shares.

In a subsequent paper, Malerba *et al.* (2001a) developed the basic model in order to debate the efficacy of economic policies in a complex environment characterised by dynamic increasing returns generated by multiple sources, that is both on the marketing side, given by a strong lock-in effect of customers, and on the production and technological side, given by the "success breeds success" story. The focus of the analysis is on the role of the antitrust policy in facing the rise of the near monopolist (IBM) in the mainframe market. The antitrust laws represent one of the main public interventions in order to control monopoly power that characterise the industry under examination[6]. In this model, then, our specific task is to consider explicitly the role of the public institutions in the evolution of the industry: we mentioned above that firms are embedded in a system where other agents like public and other private institutions are involved. This consideration, then, adds complexity to the analysis of the industry, and our simulation runs represent a way for coping with it. In particular we wanted to put the accent of our analysis on the relevance of the timing of the intervention of the Antitrust Authority.

With regard to this it is clear how the run of our exercises represent an investigative device, such that we are able to assess the question "What might have happened…", as we mentioned above, "… if the Antitrust Authority would have intervened early or late?", with the goal of giving insights and to contribute to the discussion about the role and the effect of the Antitrust laws.

In the structure of the model the antitrust policy has been implemented by letting the Antitrust Authority intervene when the monopolist reaches a market share of 75%: when this occurs the monopolist firm is divided into two new firms having half size of the budget and resources of the original monopolist.

The results of the simulation runs show that it is crucial to consider in the evaluation of the antitrust intervention's effects the size of existing firms, if there are potential players that have not entered the market yet and if the increasing returns are still quite high or not. In the case of immediate intervention (just 1 year after the monopolist has reached a market share of 75%), the market becomes concentrated again very soon, given that the increasing returns are still quire high. The not immediate intervention (after 5 years) leads to a situation in which the emergence of a monopolist takes much more time, and in the end the level of the concentration ratio is significantly reduced. The reason of this could be that the break up has the effect of making firms more similar in terms of size and resources. If the Antitrust Authority intervenes late (after 10 years), on the other hand, the largest firms has already reached a significant size such that the two resultant firms *"[…] are already rather large with respect to the other competitors: therefore, one of the two new large firms will gain the leadership and the market will tend toward concentration"* (Malerba *et al.*, 2001a). At last, if the intervention is very late (after 20 years), the increasing returns have started to fade away and consequently the market becomes a duopoly.

[6] This analysis is extremely vivid if we think about the recent debate between Microsoft and the Antitrust Authority.

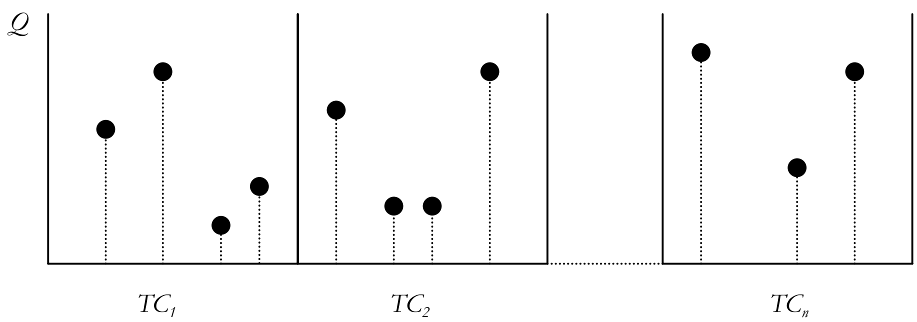
The example given above shows that in the simulation model we have developed a large number of variables and a quite complex structure of the market are considered. The flexibility of the object-oriented programming let us deal with this kind of complex systems in a tractable way.

5.2. A "History-Friendly" Model of the Evolution of the Pharmaceutical Industry

In another model (Malerba and Orsenigo, 2002; Garavaglia *et al.*, 2004) the focus of analysis is on the pharmaceutical industry. The purpose of the basic model is to capture the main features of the industry evolution, examining the differences between the so called era of random screening and the age of molecular biology. It is shown that, given the nature of the processes of drug discovery, the characteristics of the competition process, the low degree of cumulativeness and the fragmented nature of the markets, a low level of overall concentration of the industry soon emerges, and the advent of biotechnological firms does not represent a displacement of the incumbent ones.

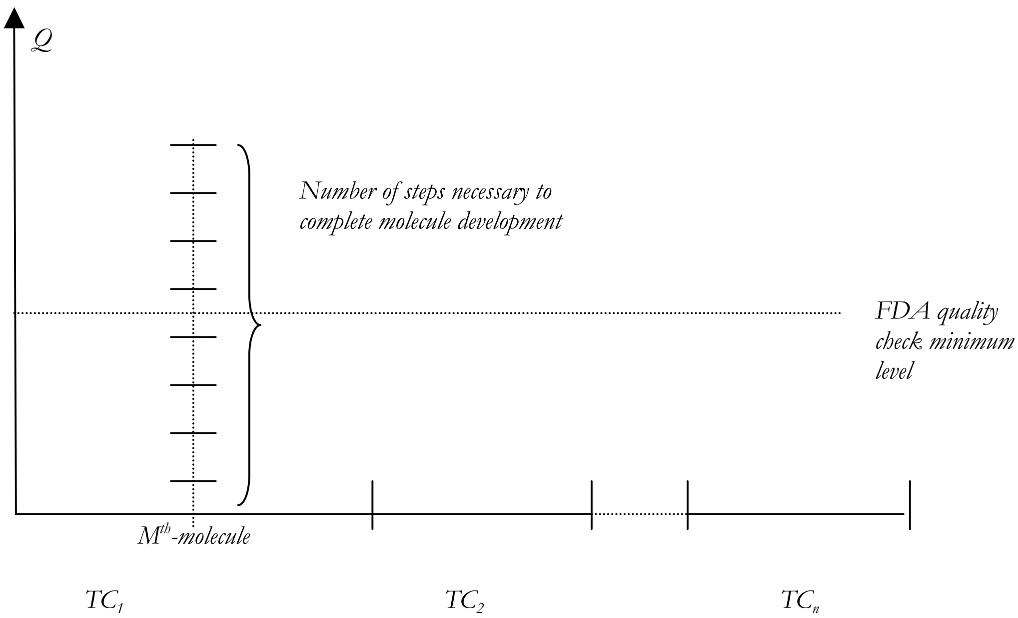
Here markets, called Therapeutic Category (TC), define the basic setting up of the model. In the TC class another class, called Molecule, is encapsulated: this class describes the basic framework of the objects "Molecules" that are the potential source for giving birth to a drug that, belonging to that given therapeutic area, will be able to cure a particular disease (Figure 3).

Figure 2: The topography of the industry



Firms are engaged in three sequential activities. In the search process firms explore the "space of molecules" until they find one that might be developed as a drug. The process of search differs for the two sets of firms in the model: incumbent pharmaceutical firms and biotechnological firms, that start operating when the biotechnological revolution occurs at time τ. For the former, the search activity is a random exploration process, while for the latter there is a more efficient process of search that enable firms to exclude some segments of the search space. The second activity is given by the development process, according to which firms start the procedure of drug development. This process is modelled by representing the potential quality *Q* of a molecule as a vertical segment in the therapeutic category area. Firms invest a share of their budget and progressively "climb" *Q* steps in order to develop a drug having a quality *Q*. After a firm reaches *Q*, the research process is terminated and, if the quality of the given molecule is greater that the minimum level required set by the political authority (FDA), the product is ready to be launched by the firm on the market (Figure 3): this is done by investing a share of the available budget in marketing activities.

Figure 3: The topology of research activities.



From this brief description of the firms' activities, and if we take into account that firms are characterised by a large set of variables and are heterogeneous, it is clear how the model is complex. In terms of the object-oriented programming we are able to define a class called "Firm" that represents the framework on which all the objects firms are defined. Each firm is defined by a large number of variables, which contribute to determine their characteristics, their behaviours and the storage of the results that emerge from their behaviours and activities.

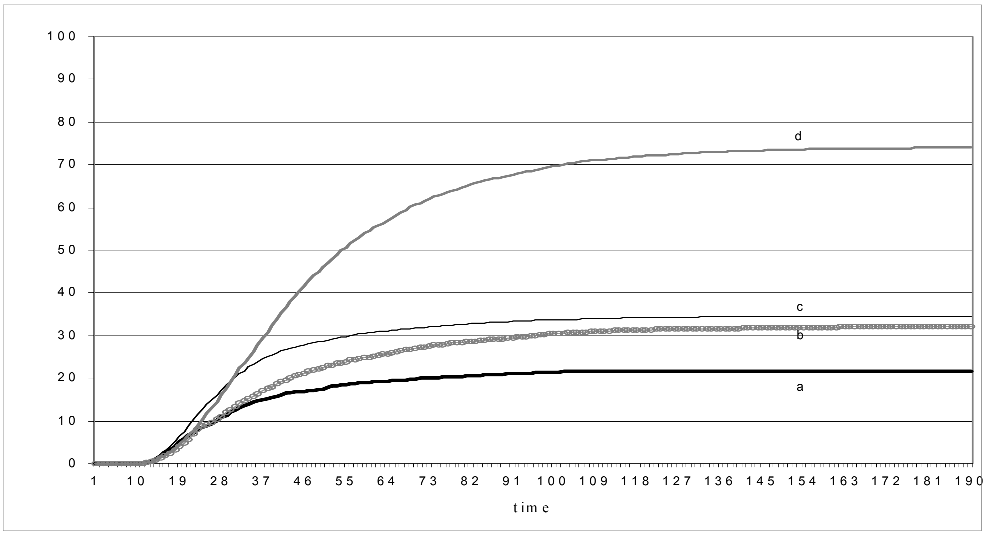
Firms' behaviours are then structured in the so called "methods", in which, for example, the processes of search, development and creation on new products are given. In the method called "search" firms divide the available amount of money among search, research and marketing activities, and determine the expenditure in search activities for the current period as a firm-specific share of the budget available for search and research. The amount of the expenditure in search activity defines, then, in another part of the program the firm's number X of therapeutic categories which are explored during the current project.

In the method called "research", consistently with the description given above, firms "climb" the quality ladder Q of the molecule explored, according to a given firm-specific speed defined by a firm-specific variable. In the method "newProduct" firms create the product and start to define the amount of resources to invest in its commercialisation. Two other simply examples of methods are the method called "failure", in which it is stated that, if a certain condition holds (given in the method "search, i.e. if the budget is lesser than zero) all the relevant variables that define the behaviour of the firms are set equal to zero, that is to say the firm fails and exit the market, and the method "accounting" in which firm's profits are divided among the usual activities. These simple descriptions of methods give us the opportunity to understand the flexibility and the complexity of the structure and functioning of the model.

The activities of the firms, as described above, aim at modelling the way of searching and developing a drug by firms in the pharmaceutical industry, as reported by several analyses and case studies.

We claimed that the motivations of the "History-friendly" approach consist in the replication, description and logical exploration of what have happened and the study of what might have happened. We also stressed the importance of keeping in mind a theory in order to use a "History-friendly" model for investigative devices. With regard to this, starting from the basic model of the pharmaceutical industry, we wanted to consider the theoretical concept of exploration versus exploitation strategies, as presented by J. March (1991), in this industry. Accordingly we further developed the basic model in which we designed the search process of firms according to two different options: the exploration strategy of new opportunities and the exploitation of old certainties (Garavaglia *et al.*, 2002). Moreover, we added complexity (and appeal, we hope) to the model considering the performance of these strategies and the main outcomes of the model in two different environments: one characterised by high opportunities, low appropriability conditions and low cumulativeness (defined by the existing theories as technological regime Schumpeter Mark I, or entrepreneurial), and the other defined by low opportunities, high appropriability conditions and high cumulativeness (technological regime Schumpeter Mark II, or routinised). Such a complex structure enabled us, first of all, to study the theory of exploration and exploitation strategies, and secondly to analyse if the outcome is more influenced by the existing technological regime or by the particular nature of the firm's strategy.

Figure 4: Evolution of the number of discovered TC



a = exploitative firms in Schumpeter Mark I regime
b = exploitative firms in Schumpeter Mark II regime
c = explorative firms in Schumpeter Mark I regime
d = explorative firms in Schumpeter Mark II regime

As expected from the theory, the results show that: explorative firms discover more therapeutic categories (Figure 4) and commercialise more innovative products than exploitative ones (explorative firms are more innovative than exploitative firms, as reported in Figure 5); in particular we can recognise a technological regime effect: both explorative and exploitative firms discover more therapeutic areas in presence of Schumpeter Mark II technological regime. On the other hand, exploitative firms are more profitable, especially in the first period of the simulations run, than explorative firms. However, profitability seems to be closely influenced by the technological regime: in presence of high opportunities (i.e. Schumpeter Mark I) profitability is higher. Worth noting is the result that shows how firms' strategy has no influence on the level of concentration in the industry, while in presence of technological regime Schumpeter Mark II we register a higher concentration ratio (Figure 6). A very rough performance index, that measures the share of the existing total quality of molecules that has been discovered, shows the effect of the technological regime Schumpeter Mark II and a better result of exploitative firms.

Figure 5: Number of explorative and exploitative innovative firms

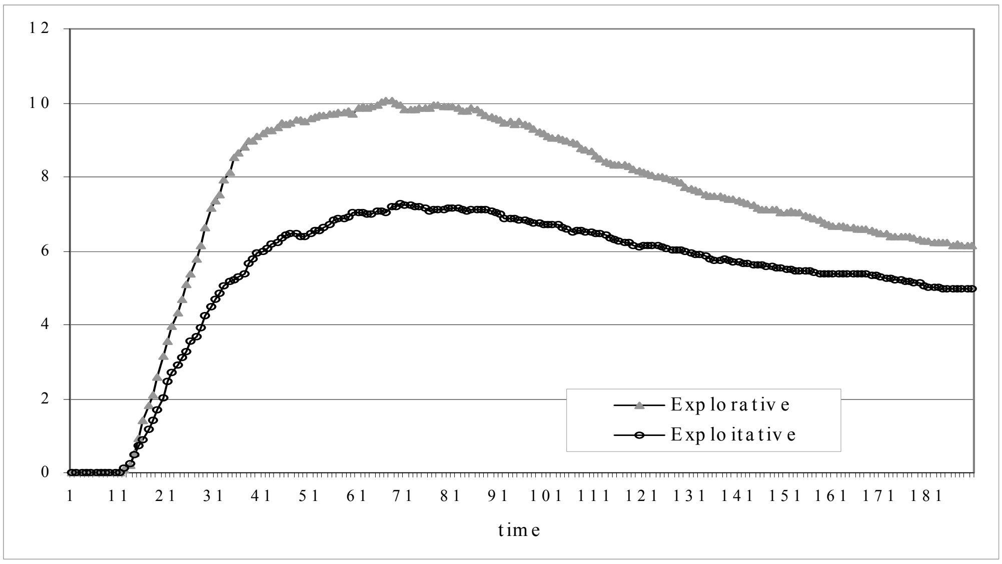
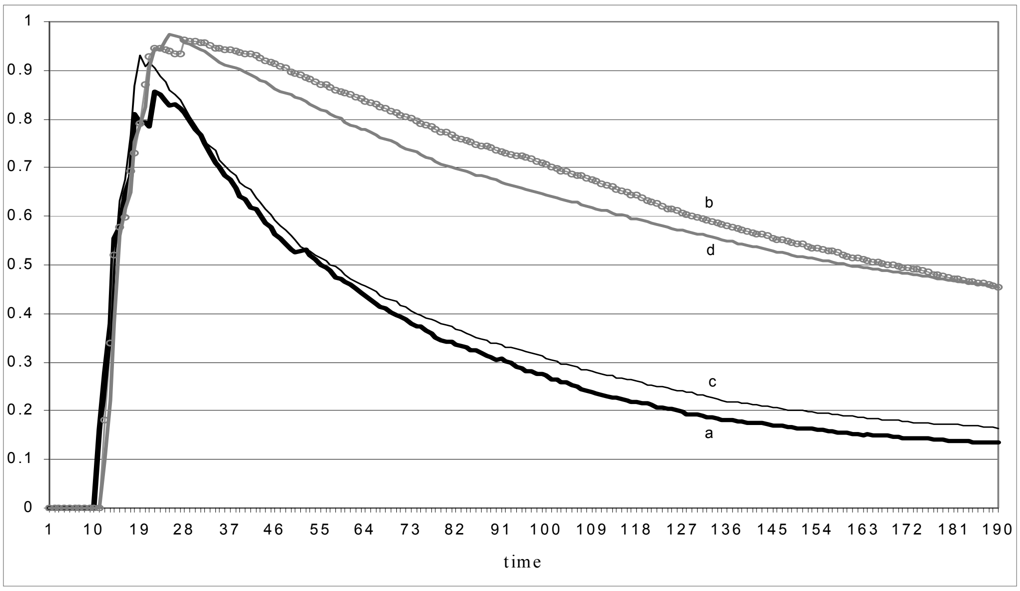


Figure 6: Herfindhal index



These preliminary results seem to suggest that explorative firms are more effective in finding and developing new drugs when the technological regime

Schumpeter Mark II characterises the economic environment. On the other hand, with regard to profitability and in terms of what we called performance index, exploitative firms seem to perform better, no matter of what is the technological regime.

We believe that the example we presented above have elucidated the basic way of proceeding in the setting up of the simulation model, and the several possibilities of modelling complexity, considering a large number of variables and activities, and testing together different theoretical approaches in order to check the links and relationship that they have on each other, with the aim of investigating the existence of some interesting joint results.

6. Conclusions and Challenges for "History-Friendly" Models

This paper aims at putting some order in the new branch of models called "History-friendly" simulation models. After a brief recall of the key principles of the industrial dynamics approach, we have described the basic features of "History-friendly" models, and we have studied the philosophy and meanings of the "History-friendly" approach.

We strongly emphasised, during the discussion, the concept of *complexity*, that characterises the economic world and its ongoing process of change, and the ability of simulation models to assess with it, as well as and the property of *emergency* of the simulation approach adopted here. We believe that these two features represent the actual essence for adopting the approach of study presented in this work.

We claim here that if the purpose of "History-friendly" models is to capture realism of the behaviour of the economic agents and their complexity, as well as to engage in dialogue with the arguments presented by the empirical analyses, then the future challenge for the followers of this approach of study will be the attempt to relate more and more closely to the empirical evidence, empirical data, case studies and business studies in the implementation and definition of the simulation model.

As we described, industry level studies constitute the first step for the development of a "History-friendly" industry-specific model. With regard to this, a lot of work has been done and a deep understanding of the basic logic and of the main features that characterise the structure and the evolution of the industries under examination has been reached. Also the analyses at firm and business level, in order to fully understand the *modus operandi* of innovative firms embedded in their competitive arenas, have been carried on so far. We claim here that the interaction between the historic and the economic perspective with the point of view of the business and management analyses would be profitable if business studies and cases might enable the researcher to understand more deeply the behaviour and functioning of a firm: calibration of parameters' values related to firms' behaviour represents at this stage a crucial point for the future of "History-friendly" models. The interpretation of the qualitative results that emerges from this approach of study would gain in applicability as well as in credibility if the theoretical structure of the model, the parameters' value and the main outcomes could also have a more quantitative flavour. For example, data about the mean share of profits invested by firms in R&D, in marketing activities and so on, would help the "History-friendly" model programmer to really give a coherent picture of the considered economic agent. Consequently the results would gain in transparency and readability.

Equally important is what we called the "third step" of the analysis, which requires, after the simulation runs, to go back to the theories and the history of the industry under exam in order to understand what are the factors that are responsible for the obtained results, to work out the hypotheses and results of the theoretical logic, thus stimulating the theoretical debate, reasoning and discussion. In other words, the aim of this third step is to sharpen the research agenda for industrial dynamics' researchers. We claim that this step needs to be carried out explicitly in the discussion of the outcomes of the simulation model.

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